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Water uptake by coniferous and broad-leaved forest in a rocky mountainous area of northern China

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ABSTRACT

Extreme drought and precipitation are expected to occur more frequently due to climate change, which may influence the water uptake patterns by vegetation in the rocky mountainous area of northern China. In this work, dual stable isotopes were used to detect the water sources of mixed forest of coniferous and broad-leaved tree species and their response of leaf water potential under differently sized precipitation events (no rain: 0.0 mm; light rain: 9.8 mm; moderate rain: 21.8 mm; large rain: 31.6 mm and rainstorm: 51.2 mm). The results showed that *Platycladus orientalis* and *Quercus variabilis* had different water use strategies and opposite responses to precipitation. On dry (no rain) days, *P. orientalis* and *Q. variabilis* predominantly obtained water from natural springs (43.3% and 36.2%, respectively) and deep soil layer (32.8% and 31.3%, respectively), while *Q. variabilis* also used water from shallow soil layer (23.4%). Following the rainfall events, the *P. orientalis* with dense and shallow fine root system absorbed more water from the soil surface layers (23.1–33.5%) and precipitation (15.2–30.7%). The pre-dawn water potential (ψ_{pd}) and the midday water potential (ψ_{md}) of *P. orientalis* increased with the amount of rainfall, revealing a sensitive response to precipitation. On the other hand, *Q. variabilis* mostly took up water from natural springs (32.3–36.7%) and deep soil layer (33.8–37.1 %) after the rainfall events through its well-developed taproot system. The ψ_{pd} and ψ_{md} of *Q. variabilis* had no significant variation between no rain and light rain events, though they increased significantly for large rainfall and rainstorm events with > 60 cm of soil water recharge provided by the precipitation. The study provides more insights into reforestation and water management in the region of northern China.

1. Introduction

Precipitation is the primary water source for mountainous forest ecosystems and can determine vegetation distribution, growth and water utilization, which fundamentally affect nearly all hydrological processes within the ecosystem (Zhang et al., 2011; Kray et al., 2012; Liu et al., 2015; Tao et al., 2017). The amount of precipitation may be a critical factor affecting the water sources of trees. Small rainfall events or precipitation with short pulses, which moisten the surface soil layer, is easily lost through evaporation (Dunkerley, 2015). Trees only make use of this water source if they have absorbing roots near the soil surface. Large precipitation events can penetrate the deeper soil layers, which is beneficial to the deep-rooting plants that utilize deep soil water (Meier et al., 2017). Meanwhile, it has also been demonstrated that different tree species may exhibit contrary water use patterns in response to precipitation variations (Williams and Ehleringer, 2000; Yang et al., 2011; Wu et al., 2015). Several trees are able to rapidly obtain considerable amounts of soil water, recharged by rainfall, and the proportion of precipitation absorbed by certain tree species increased as the amount of rainfall increased (Lin et al., 1996; Williams and Ehleringer, 2000). Nevertheless, several tree species exhibited strong dependence on the soil water, while some obtained water from groundwater regardless of the precipitation throughout the growing season (Kray et al., 2012; Wu et al., 2016a,b; Liu et al., 2018). The responses of trees to precipitation are determined in part by the characteristics of rainfall (duration, intensity, and amount), and also depend on physiological characteristics, root morphology and structure of trees (Poot and Lambers, 2008; Dai et al., 2015). Many trees have developed a dimorphic root system, which is made up of surface roots that can acquire water from upper soil layers, and the deeper roots that can exploit water from deeper soil layers or groundwater (Yang et al., 2011; Wu et al., 2015; Evaristo et al., 2016). It has been suggested that the leaf water potential (ψ) of some tree species also clearly respond to rain pulse events (Xu and Li, 2006; Song et al., 2016). The ψ of some tree

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species has a good correlation with the soil's moisture status in rhizosphere and can effectively reflect the water status of plants (Stahl et al., 2013; Dai et al., 2015).

The *Platycladus orientalis* and *Quercus variabilis* are typical plantation tree species in northern China. Precipitation in this area exhibits a clear seasonal variability. Correspondingly, the availability of soil moisture to trees in this region is highly variable with regards to both the timing and the amount (Jiang et al., 2017). Extreme precipitation events will become frequent due to climate change (IPCC, 2013; Li et al., 2013; Wu et al., 2016a,b). This may lead to a competitive interaction for water within the fixed forests experiencing a long period of drought. In addition, the water sources for trees may differ due to the variation in different precipitation events. Therefore, understanding the water use patterns of artificial mixed forests is critical for exploring the vegetation responses to these temporal and spatial changes in seasonal precipitation. A number of previous studies were primarily focused on the water source of pure forest (a forest of single tree species) under relatively stable water conditions (Jia et al., 2017; Liu et al., 2017) and the effect of seasonal drought on pure forest (Jia et al., 2013) in the Beijing's mountainous area. However, it is unclear how the water uptake of mixed forests responds to seasonal changes in precipitation. In the current study, a hydrogen and oxygen isotope (δ^2H and δ^{18}O) technique was used to: (i) evaluate water uptake patterns of mixed coniferous and broad-leaved forests (which grow together in plots) under different precipitation events; (ii) investigate how the ψ of species responds to different precipitation events in a rocky mountainous area of northern China. The first hypothesis is that the water source for both the species varies with the amount of rainfall, while the second hypothesis is that the response of $\psi$to rainfall is closely related to the water source, and is coupled with the soil moisture.

2. Materials and methods

2.1. Study site

This study was carried out in a rocky, mountainous area of the Forest Ecosystem Research Station of Capital Circle located in Jiufeng National Forest Park (40°03´ N, 116°05´ E), 30 km west of Beijing, North China (Fig. 1). The study area is 16 km^2 and is strongly influenced by warm and temperate semi-humid, semi-arid continental monsoon climate. The annual mean temperature is 11.6 °C and about 70% of the annual average precipitation (660 mm) occurs during the wet season (June - September). The study site belongs to a seasonal drought area and experiences a pronounced dry season (October - June) when monthly total precipitation remains below 25 mm. The annual potential evapotranspiration is as high as 1100 mm. The percentage of forest cover in the study area is 85%. The average age of the trees in the forest is 55 years. The artificial mixed forest of *P. orientalis* and *Q. variabilis* is widely distributed in this area. The *P. orientalis* is an evergreen coniferous species, while *Q. variabilis* is a deciduous broad-leaved tree species. According to a survey conducted in 2012, the average diameters at breast height for *P. orientalis* and *Q. variabilis* were 7.6 cm and 11.6 cm, respectively, and the mean heights were 7.2 m and 9.2 m, respectively. The undecomposed litter has the thickness of about 0.5 cm under the forest. The study area has a thinner soil layer with the average depth of 60 cm. The soil type of the two species is leached cinnamon soil, which contains high levels of humus in the 0–10 cm soil layer. The texture of the 20–40 cm soil layer is mainly clay with the lower density of gravel. The deeper soil layer (> 40 cm) is mainly loam with the higher density of gravel (Table 1).

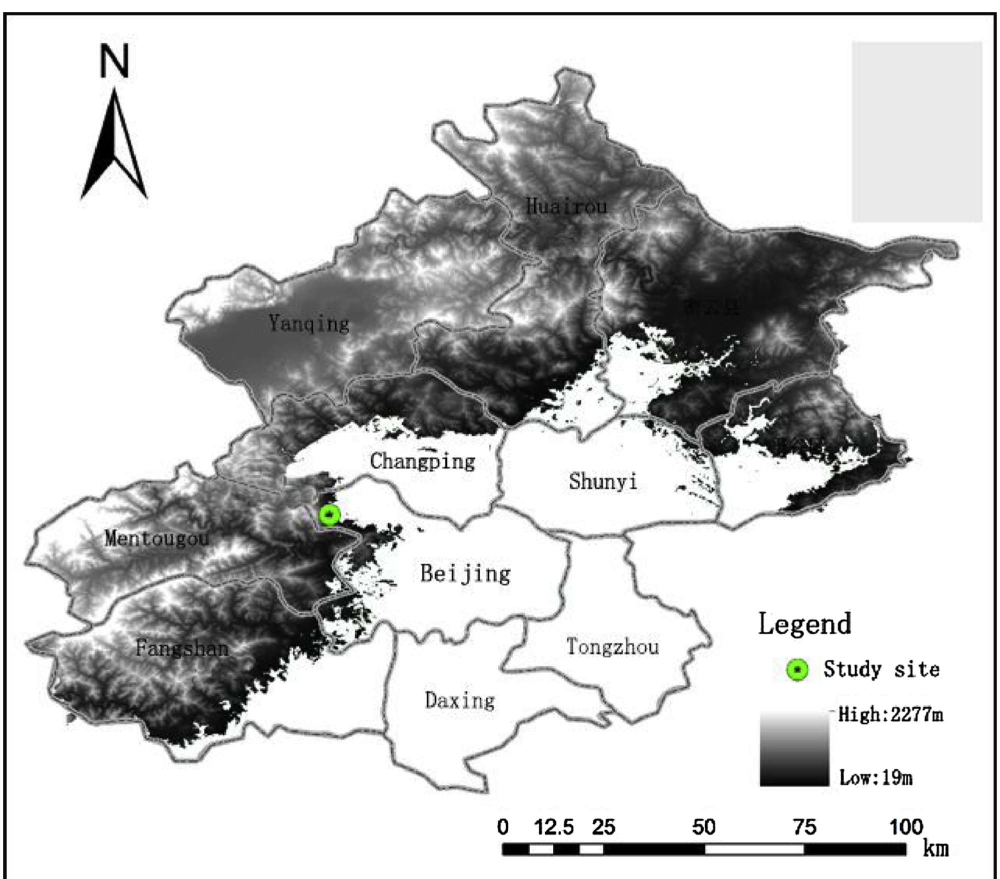

Fig. 1. Geographical location of the study area.

Table 1
Quality ratio of different forms of soil aggregates (%).

Soil layer (cm)	Diameter class (mm)						Gravel (%)
	< 0.25	0.25-0.5	0.5-1	1-2	2-5	> 5	
0–10	4.1	6.61	19.13	20.45	17.3	32.4	3.58
10–20	4.94	6.68	14.57	15.44	19.13	39.25	6.44
20–40	7.05	7.13	17.6	20.63	22.3	25.29	19.91
40–60	4.95	5.87	15.71	21.15	30.23	22.09	24.09
60–80	3.87	9.11	8.66	15.31	24.11	28.96	29.65
> 80	4.51	10.89	27.28	16.60	15.85	24.87	37.57

2.2. Sampling of branches, soils, and natural spring

Tree branches and soils were sampled on clear days (one day after the last rainfall) over a five-month period from May to October in 2013 for measured hydrogen and oxygen isotopic compositions. During the sampling period, four rainfall measurements were conducted, including 9.8 mm (light rainfall), 21.8 mm (moderate rainfall), 31.6 mm (heavy rainfall) and 51.2 mm (rainstorm) under differently sized precipitation events. In addition, a sunny day (0.0 mm) was chosen for comparison purposes.

The sample collection of branches and soils was conducted in four 20 m × 20 m experimental plots. The four plots contained only two species of *P. orientalis* and *Q. variabilis* (Fig. 2). There was a gap of 50 m between the experimental plots and the distance between the successive trees was about 2.8 m. In each experimental plot, three trees of each species (*P. orientalis* and *Q. variabilis*) were randomly selected at each time. Three suberized twigs (3–5 cm long and 0.3–0.6 cm in diameter) were cut from each tree, which were in the same direction and at the same distance from the ground (there were nine twigs from each species per plot in total, and the results were the average the three measurements per tree.). Near the selected tree species (< 0.5 m), three soil sampling points were chosen and the samples were collected at the depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, 60–70 cm, 70–80 cm, and 80–100 cm using soil drilling. Three samples per tree and three samples per soil layer were collected at a time, and the bark on the branches was removed immediately before placing them into clean polyethylene bottles (50 ml), which were sealed with Parafilm M®, stored, and frozen for isotopic analysis. The collection point of natural spring was Jinshan temple, which was located 1.3 km from the sampling trees. On the same day of the collection of soil samples, three natural spring samples were collected in 50-ml plastic test tubes at a time and wrapped in Parafilm M®, then stored in a frozen state to avoid evaporation fractionation.

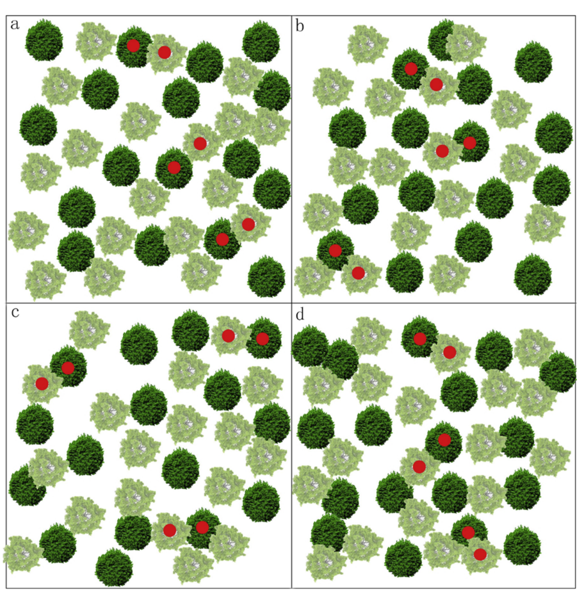

Fig. 2. Relative position of *P. orientalis* and *Q. variabilis* in four experimental plots. The symbols a, b, c and d were the selected plots. The red dots were the selected sampling trees (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2.3. Data collection

Precipitation data in the study area were collected from a forest weather station HOBO (U30-NRC, Onset, USA), which was 1 km away from the experimental plots. ECH$_2$O moisture sensors (Decagon, USA) for soil water content (SWC) were installed at 20 cm depth intervals (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm) and connected with the EM50/R data collector (Decagon, USA). The data collector was set to automatically record a data point every 10 min and an average of these data points was calculated every 30 min. The results of SWC were the average of 48 collected data points in a day to better reflect the response of soil moisture to precipitation changes.

2.4. Sampling of precipitation

Three iron collection buckets were placed near the weather station with no surrounding barriers to collect the precipitation samples. At the top of each collection bucket, a funnel containing a table tennis ball was added to avoid isotopes' evaporation fractionation. The precipitation samples were collected one day after the end of each rainfall event. The collected samples were quickly transferred to clean polyethylene bottles (50 ml), which were sealed with Parafilm M®, numbered, and refrigerated.

2.5. Leaf water potential measurement

On the day before the rainfall (D$_0$), first day after rainfall (D$_1$) and the second day after rainfall (D$_2$), at the top of the canopy of *Q. variabilis* and *P. orientalis*, leaves were cut randomly before dawn (0400–0600 h) and midday (1100–1300 h) every 30 min. Additionally, the leaves were tailored to the sample chamber size, and placed in a WP4C (Decagon, USA) for ψ measurements. There were five leaves per tree. Three measurements were made at predawn and midday for each leaf. Then, every measurement was averaged for every leaf to obtain the results for each tree. The measurement accuracy of the WP4C was ± 0.05 MPa.

2.6. Investigation of the root systems

The 1/4 circle digging method was used to investigate the root system after taking isotopic samples (Angadi and Entz, 2002). With the intention of minimizing the destruction, only three trees in each species were excavated to investigate the root biomass. For each tree, the soil profile with the 80 cm depth at 20 cm intervals in the vertical direction and 200 cm in the horizontal direction was excavated by soil corer (50 cm × 50 cm × 20 cm). The roots were distinguished from soil and washed with water. They were divided into diameter (d) categories of < 2.0, 2.0–5.0 and > 5.0 mm for each soil layer. The root biomass was determined using a conventional oven-drying and weighing method. The proportion of root biomass (PRB) was the weight of each diameter categories, which accounted for the percentage of total root weight of the survey.

2.7. Hydrogen and oxygen isotope analysis

Firstly, the water was extracted from branch and soil samples using a cryogenic vacuum distillation system (West et al., 2006). Then, the hydrogen and oxygen isotopic values for all the liquid samples, including the branch extracts, soil water extracts and precipitation, were

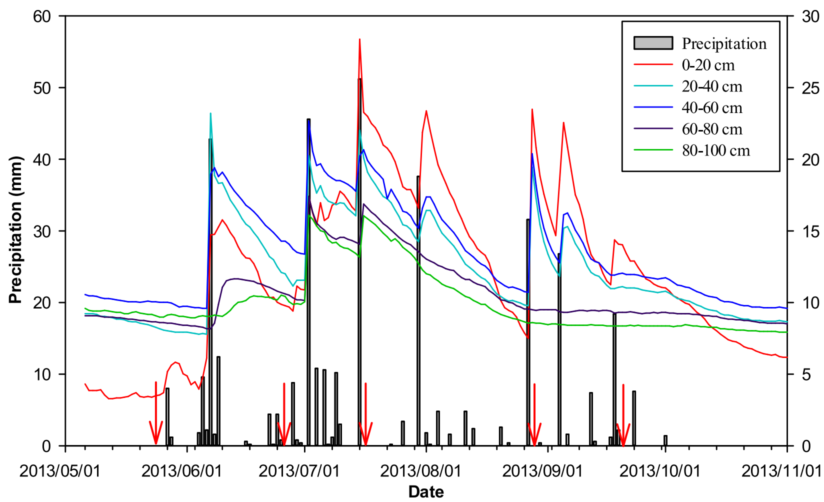

Fig. 3. Variation in precipitation and mean SWC during the growing season at the study site. The downward arrows represent the sampling dates.

measured using a liquid water isotope analyzer (LGR DLI-100, USA) at the laboratory of eco-hydrological processes and mechanisms, Beijing Forestry University, China. The measurement accuracy of the instrument was ± 0.32‰ for ^{2}H and ± 0.17‰ for ^{18}O. The isotopic values were normalized to Vienna Standard Mean Ocean Water (VSMOW) scale and reported in the units of standard per mil (‰) relative to VSMOW. The isotopic concentrations were expressed using Eq. (1).

$$\delta^2H/^{18}O = \left(\frac{Rsample}{Rstandard}\right) \times 1000‰ \tag{1}$$

where R_{sample} and $R_{standard}$ represent the values of (^{2}H/H or ^{18}O/^{16}O) for sample and the standard (VSMOW), respectively.

2.8. Statistical analysis

The multi-source model (Iso-Source) was used to calculate the contribution ratio of water sources for tree species based on isotopic mass conservation theory (Phillips and Gregg, 2003). The soil layers with similar isotopic values were merged into the same water source. The δ^2H and δ^{18}O values of precipitation, surface soil layer (0–20 cm), middle soil layer (20–60 cm), deep soil layer (60–100 cm) and natural spring water were calculated using the model to reduce experimental error and increase the accuracy of calculation. The equations for calculating the contribution ratio can be expressed using Eqs. (2) and (3).

$$\delta X_T = c_1\delta X_{S1} + c_1\delta X_{S2} + c_1\delta X_{S3} + c_1\delta X_{S4} + c_1\delta X_{S5} \tag{2}$$

$$c_1 + c_2 + c_3 + c_4 + c_5 = 1 \tag{3}$$

where δX_T is either the δ^2H or δ^{18}O value in the xylem water. The subscripts S1–S5 are the source's precipitation, surface, middle, deep soil layer and groundwater, respectively. Additionally,c_1-c_5 are the contribution ratios of S1–S5 for total xylem water absorption.

Statistical analyses were performed using SPSS 16.0. Descriptive statistics were used to calculate the means and standard deviations for each set of replicates. Firstly, two-way ANOVAs were used to analyze the differences in the soil water content (n = 48 for each soil stratum), isotopic composition (n = 36 for each soil stratum) with the amount of rainfall and soil depth as the independent factors. A two-way ANOVA was also performed to test the effect of tree species and the sampling time on ψ (n = 135 for each sampling date). Then, three-way ANOVA was used to analyze the differences in PRB (n = 3 for each soil stratum) using the diameter, species and soil depths as the independent factors. The least significant difference was employed to examine the PRB when necessary. Regression analyses and t-test were used to identify relationships between ψ and soil moisture, and between ψ and water source. R^2 and P-values were also estimated. All data were tested for normal distribution and homogeneity of variance analysis, which meet the requirements of variance analysis.

3. Results

3.1. Seasonal variations of environmental parameters

The study area was a typical seasonal drought area in northern China and there was a clear seasonal variation in precipitation. About 75.3% of the precipitation was concentrated in the time period of June – September, which is known as the rainy season (other months are referred to as the dry season) (Fig. 3). There was no rain, light rain, moderate rain, large rain and rainstorm of precipitation prior to the sampling dates of May 25, June 26, September 20, August 28, and July 16, respectively, and the corresponding average soil profile SWC values were 7.86%, 10.97%, 11.42%, 16.28%, and 19.39%, respectively. In the sampling period of no precipitation, the SWC in the 0–20 cm layer was significantly lower than in the deeper soil layer (F = 5.03, P = 0.015). The SWC at all five soil layers increased by different degrees after receiving rainfall and decreased at the end of the precipitation. After the light rainfall, the SWC increased by 64.22% in the 0–20 cm layer. However, there was no significant change in the SWC of other soil layers (P > 0.05). After the rainstorm, the SWC increased in all five soil layers. However, the SWC increase in the deeper layers had a time lag relative to the shallow layers.

3.2. Isotopic characteristics of precipitation, soil water, and stem water

The local meteoric water line (LMWL; δ^2H = 6.70 δ^{18}O –1.93; R^2 = 0.93, N = 89) and the soil water content line (SWCL; δ^2H = 4.25 δ^{18}O –32.05; R^2 = 0.76; N = 147) were obtained based on the isotopic values of precipitation and soil water samples in the study area (Fig. 4). Relative to the global meter water line (GMWL), which is expressed as δ^2H = 8δ^{18}O + 10 (Craig, 1961), the LMWL and SWCL had lower slope and intercept values. In addition, the slope and intercept of the SWCL were lower than those of the LMWL. The values of δ^2H and δ^{18}O in xylem water were less than those of the LMWL and close to those of the SWCL, which reflected a degree of fractionation in xylem water and implied that it mainly came from soil water. The hydrogen and oxygen isotopic compositions of precipitation (–105.22 to –13.96‰ and –14.43 to –0.51‰, respectively) were significantly different from those in the soil water (–83.86 to –28.19‰ and –11.33 to 1.90‰, respectively) during the growing season (F = 4.92, P = 0.013). The values of δ^2H and δ^{18}O for natural spring water were located along the GMWL and LMWL, indicating that the natural spring was supplemented directly by

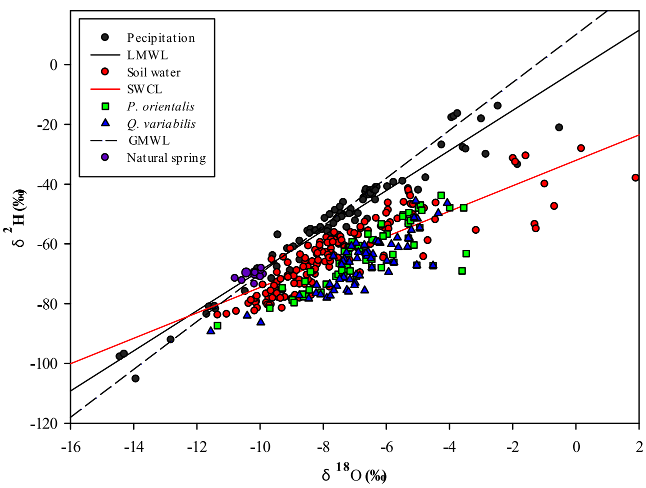

Fig. 4. Values of δ^2H as a function of $\delta^{18}O$ for water sources and tree xylem (*Q. variabilis* and *P. orientalis*) during the growing season at the study site. The global meter water line (GMWL, $8\delta^{18}O + 10$), soil water content line (SWCL, $\delta^2H = 4.25\ \delta^{18}O - 32.05$) and local meteoric water line (LMWL, $\delta^2H = 6.70\ \delta^{18}O - 1.93$) in 2013 are plotted for reference.

the precipitation. Meanwhile, Fig. 4 suggested that there was little variation in the isotopic composition of natural spring during the sampling period.

3.3. Variation in isotopic composition of soil water and natural spring

The isotopic composition of soil water exhibited rainfall effects and a vertical change downwards the soil depth (Fig. 5). In general, the isotopic values of soil water were more depleted with the greater amount of precipitation. During no and light rainfall events, there was a large variation in isotopic composition in the 0–40 cm soil layer and the values of δ^2H and $\delta^{18}O$ of soil water decreased with the soil depth. Relative to light rainfall events, the values of δ^2H and $\delta^{18}O$ of soil water increased with the soil depth in the0–40 cm soil layer and decreased with the soil depth in the 40–80 cm soil layer during moderate rainfall events. In contrast to the no rainfall to moderate rainfall events, the isotopic values of soil water exhibited little change in the 0–40 cm soil layer and gradually decreased with the soil depth in the 40–80 cm soil layer during large rainfall and rainstorm events. The isotopic composition of 80–100 cm soil water and natural springs changed slightly across the sampling periods, which was more depleted than in the other soil layers.

3.4. Distribution characteristics of root systems

The PRB of the two tree species exhibited different vertical variations in the soil profile. *P. orientalis* exhibited an extensive network of lateral roots in the surface soil layer (Fig. 6). The PRB of *P. orientalis* in the 0–20 cm soil layer was 45.0%, which was significantly higher than that in the 60–80 cm soil layer (9.9%) ($F = 26.49$, $P = 0.001$). In the 0–20 cm soil layer, the PRB of *P. orientalis* for $d < 2$ mm was 13.9%. It was not significant with the $d = 2–5$ mm ($F = 3.36$, $P = 0.626$). However, it was significantly lower than that of $d > 5$ mm ($F = 4.70$, $P = 0.039$). Different from *P. orientalis*, *Q. variabilis* exhibited a well-developed taproot system. The PRB of $d > 5$ mm was significantly higher than that of $d < 2$ mm and $d = 2–5$ mm throughout the soil profile ($P < 0.05$). The PRB of *Q. variabilis* for $d > 5$ mm accounted for 79.2% of the total root system. However, the PRB of $d < 2$ mm and $d = 2–5$ mm was less than 1% in the 60–80 cm soil layer.

3.5. Feasible contributions of potential water sources after rainfall

The calculation results of Iso-sources (multi-source model) showed that the two tree species used precipitation differently in diverse rainfall event (Fig. 7). During no rainfall event, both the species primarily obtained water from the deep soil layer (32.8% and 31.3%, respectively) and natural springs (43.3% and 36.2%, respectively). At the same time, the *Q. variabilis* used water from the surface soil layers (23.4%). With an increase in the rainfall, the *P. orientalis* absorbed more surface soil water and precipitation instead of deeper water. The proportion of surface soil moisture, used by *P. orientalis*, reached 33.5% during heavy rainfall events. The proportion of precipitation, used by *P.*

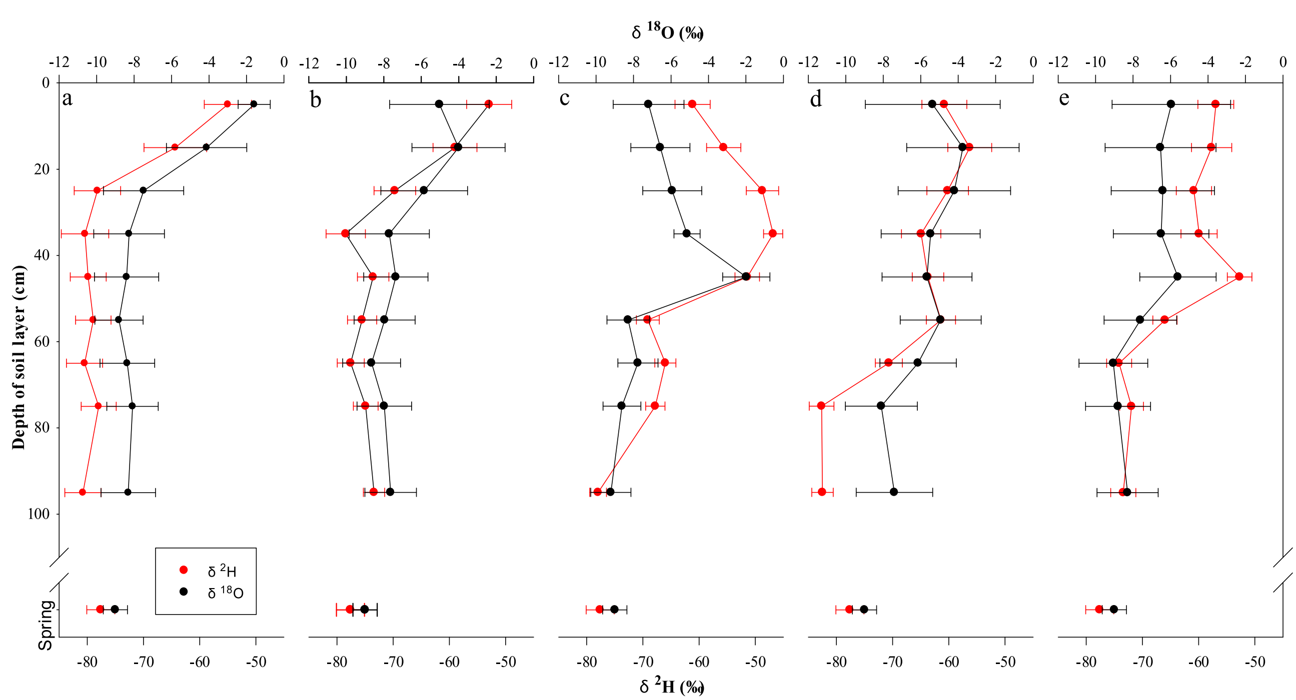

Fig. 5. Variation in mean (± S.D.) δ^2H and $\delta^{18}O$ along the soil profile during the growing season. The symbols **a**, **b**, **c** **d** and **e** represent no rain, light rain, moderate rain, large rain, and heavy rain, respectively.

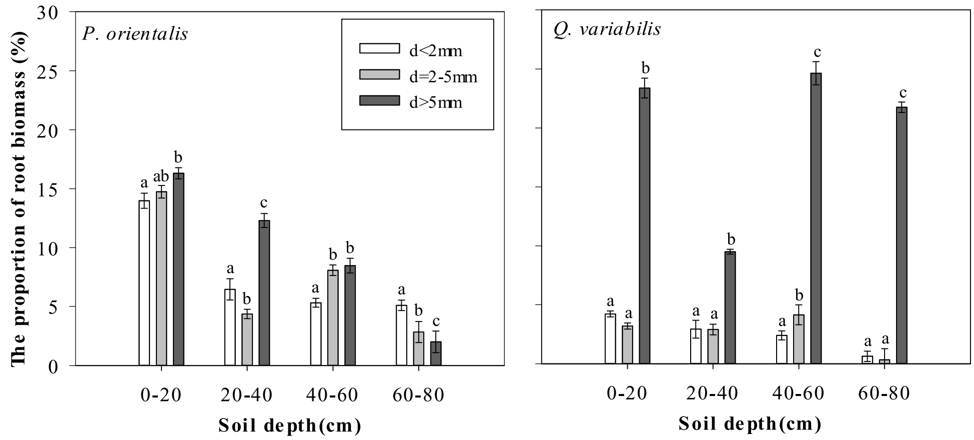

Fig. 6. Mean (± S.D.) proportion of root biomass with different diameters in the soil profile. Here, *d* indicates the root diameter. The different letters indicate significant differences in PRB among the root diameter within the same soil layer.

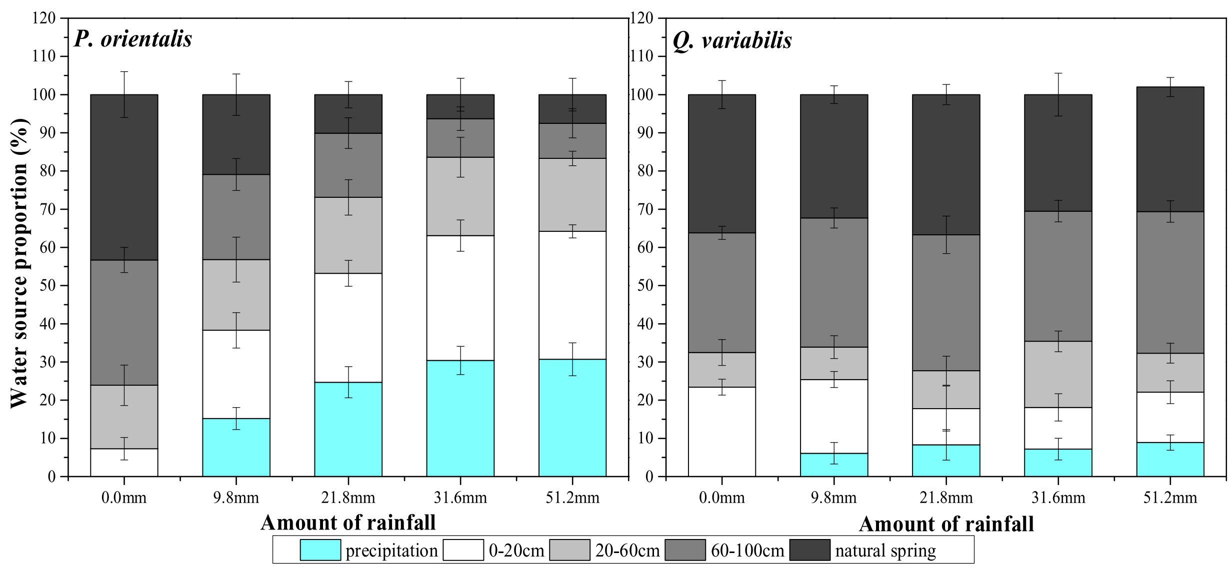

Fig. 7. The mean (± S.D.) water source proportions for *P. orientalis* and *Q. variabilis.*

orientalis, increased from 15.2% (light rain event) to 30.4% (moderate rain event). However, it did not increase from large rain to rainstorm. On the other hand, *Q. variabilis* used water mostly from the deep soil layer and natural springs under differently sized precipitation events. However, the rainfall absorbed by *Q. variabilis* did not change with the amount of rainfall, and the average proportion of precipitation used by *Q. variabilis* was 7.6% under differently sized precipitation events.

3.6. Variation in leaf water potential

The ψ_{pd} and ψ_{md} of the two species exhibited seasonal variation during the sampling period (Fig. 8). As Fig. 8 suggested, the values of ψ_{pd} (−4.37 ± 0.60 MPa) were significantly higher than those of ψ_{md} (−6.98 ± 0.96 MPa) in the same tree species during the sampling period (F = 4.88, P = 0.019). Overall, the ψ_{md} values of *P. orientalis* were higher than those of the *Q. variabilis*. The values of ψ_{pd} and ψ_{md} for *P. orientalis* increased with the increase in precipitation and reached their maximum values (−3.65 and −5.50 MPa, respectively) after the rainstorm events. The variation in ψ_{pd} and ψ_{md} (−4.85 ± 0.08 and −8.18 ± 0.04 MPa, respectively) for *Q. variabilis* had no significant variation during no rain to moderate rainfall events (F = 2.36, P = 0.128). However, they have stronger correlation coefficients between heavy rainfall and rainstorm events (F = 5.53, P = 0.009).

The values of ψ_{pd} and ψ_{md} for *P. orientalis* showed significantly correlation with surface soil moisture, but the values of ψ_{pd} and ψ_{md} for *Q. variabilis* showed significantly correlation with deep soil moisture (Table 2). The stronger relationship between ψ_{pd} for *P. orientalis* and surface water source (precipitation and 0–20 cm soil layer) indicated that the ψ_{pd} increased with the *P. orientalis* uptake more surface water and precipitation (Table 3). The negative relationship between ψ_{pd} for *P. orientalis* and deep water source (60–100 cm soil layer and natural spring) indicated that the ψ_{pd} decreased with the *P. orientalis* uptake more deep water source. The weaker relationship between ψ_{pd}/ψ_{md} of *Q. variabilis* and water source indicated that leaf water potential was less associated with water source.

4. Discussion

4.1. Water uptake of tree species under precipitation events

The results suggested that *P. orientalis* and *Q. variabilis* were very plastic with regards to the absorbed water sources and exhibited different responses to precipitation (Fig. 7). This result was consistent with the findings of previous studies, which reported that *P. orientalis*, having a dimorphic root system, can change the water source based on soil moisture (Jia et al., 2013; Liu et al., 2017). During days of no rainfall,

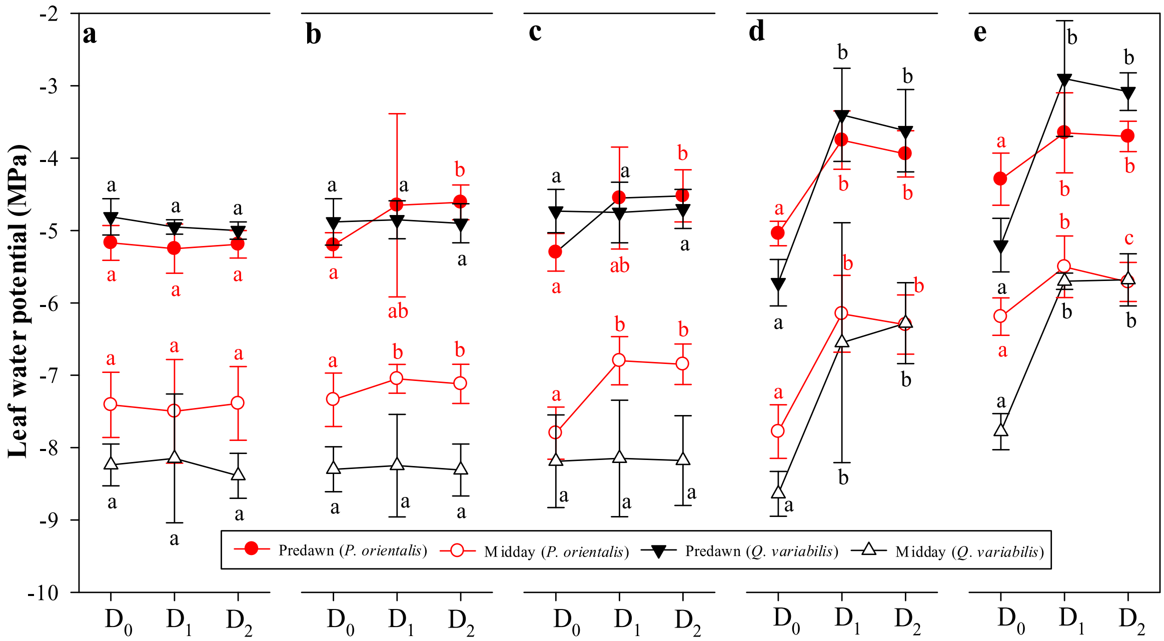

Fig. 8. Variation in mean (± S.D.) leaf water potential for *P. orientalis* and *Q. variabilis* during the growing season. The a, b, c, d and e were no rain, light rain, moderate rain, large rain and rainstorm, respectively. The D_0, D_1 and D_2 were the one day before the rainfall, first day after rainfall and the second day after rainfall, respectively.

Table 2
Parameters of the linear regression of leaf water potential against soil moisture of tree species (y = b + a × x).

Independent variable	ψ_{pd} (*P. orientalis*)		ψ_{md} (*P. orientalis*)		ψ_{pd} (*Q. variabilis*)		ψ_{md} (*Q. variabilis*)	
	R^2	*a*	R^2	*a*	R^2	*a*	R^2	*a*
0–20 cm	0.871**	0.080	0.783**	0.091	0.340*	0.173	0.490*	0.259
20–40 cm	0.875**	0.133	0.839**	0.157	0.297	0.170	0.429*	0.254
40–60 cm	0.853**	0.140	0.844**	0.168	0.676**	0.171	0.803**	0.232
60–80 cm	0.445*	0.145	0.604**	0.204	0.667**	0.096	0.734**	0.125
80–100 cm	0.348*	0.134	0.5277*	0.200	0.706**	0.163	0.830**	0.221

** $P < 0.01$.
* $P < 0.05$.

Table 3
Parameters of the linear regression of leaf water potential against water source of tree species (y = b + a × x).

Independent variable	ψ_{pd} (*P. orientalis*)		ψ_{md} (*P. orientalis*)		ψ_{pd} (*Q. variabilis*)		ψ_{md} (*Q. variabilis*)	
	R^2	*a*	R^2	*a*	R^2	*a*	R^2	*a*
Precipitation	0.933*	0.285	0.879*	0.191	0.580	0.113	0.516	0.142
0–20 cm	0.919*	0.207	0.858*	0.224	0.523	–0.095	0.451	–0.145
20–60 cm	0.769	0.109	0.633	0.128	0.562	0.108	0.500	0.159
60–100 cm	0.970*	–0.264	0.925*	–0.163	0.647	0.126	0.620	0.138
Natural spring	0.881*	–0.272	0.609	–0.137	0.649	0.086	0.601	0.161

* $P < 0.05$.

the water absorption activity of root hair was limited due to the dry and hot conditions in the shallow layer (Zhou et al., 2015). *P. orientalis* absorbed deeper water with higher SWC, as well as the water from relatively stable natural springs to maintain its normal physiological activity. This water use pattern has also been found in other tree species (Turner, 2002; Yang et al., 2011; Wu et al., 2015). After the rain events, the absorption ratios to surface water and precipitation increased with the increase in rainfall. This suggests that *P. orientalis* was sensitive to precipitation. A previous study at the same site as of current work also found that *P. orientalis* prefers to obtain water that was more accessible and depends more on precipitation after frequent rainfall events (Jia et al., 2013). The water use pattern of *P. orientalis* was probably related to its root system and physiology (Zhao et al., 2006). Although the root system of *P. orientalis* can reach the 60–80 cm soil layer, most of it was distributed in the 0–20 cm soil layer (Fig. 6). The water absorption activity of fine root hairs of *P. orientalis* may be activated when the soil reaches a certain humidity and temperature. Schwinning and Ehleringer (2001) reported that the key factor in responding to precipitation was the metabolic activity of roots in the upper soil layer.

Relative to the multiple water sources of *P. orientalis*, the water sources of *Q. variabilis* remained unchanged with the increase in rainfall. This water use pattern of *Q. variabilis* may be due to its long-term

adaptation to its environment and the distribution of its root system. Liu et al. (2016) suggested that *Q. variabilis* is a deciduous broad-leaved tree species with greater transpiration than the coniferous trees of *P. orientalis* in the current study site. It only obtained more water from deep soil layer and natural springs to ensure a continuous water supply since the SWC in shallow soil layer was lower during the no rain days. David et al. (2013) also found that *Quercus suber* exhibited the same water-use pattern. The long-term stability of natural springs and deep water may encourage tree species to predominantly develop roots in the saturated zone (Ehleringer and Dawson, 1992; Snyder and Williams, 2000). The small amount of shallow soil water absorption by this species may be due to two reasons. First, although the deep soil layer has higher SWC, the energy required to take up water from the deep layer is greater than that of the upper layers (Williams and Ehleringer, 2000; Schenk and Jackson, 2002a). Second, the nutrient content of the surface soil is higher due to rich humus (Gebauer and Ehleringer, 2000; Sun et al., 2014). Therefore, the species uptake of shallow soil water not only reduced its energy losses, but also provided improved opportunity for nutrient uptake (Neumann and Cardon, 2012). After the rainy events, the water use pattern of *Q. variabilis* was little different with the findings of Liu et al. (2017). The main reason for the difference between them was probably the soil moisture and the time of precipitation. In Liu et al. (2017)'s study, although there was the higher average SWC (about 16%) at the sampling date of 10 days' post-rainfall, *Q. variabilis* may have already shifted to relatively stable SWC. In the current study, the sampling dates were one day after the rainfall and *Q. variabilis* may not have had enough time to the sudden increase in soil moisture. This caused *Q. variabilis* to maintain the same water strategy as in the periods of drought, where it absorbs spring water and deep soil water was greater than that of the other soil layers.

4.2. Tree species' response to precipitation

The ψ_{pd} and ψ_{md} of *P. orientalis* and *Q. variabilis* exhibited different responses to soil moisture and water sources after precipitation (Fig. 8). The ψ_{pd} and ψ_{md} for *P. orientalis* were highly sensitive to moisture and water sources, especially in surface soil layer. The ψ_{pd} and ψ_{md} of *Q. variabilis* showed strong relationships with soil moisture in deep soil, but exhibited no significant correlation with water sources (Tables 2 and 3). The ψ_{pd} and ψ_{md} of *P. orientalis* increased with the increasing moisture of shallow soil layers (Fig. 8). Prior studies also found that other plants, such as *Bunge and Reaumuria soongorica, Chrysothamnus nauseousus,* and *Sarcobatus vermiculatus* also absorb considerable precipitation and their ψ_{pd} and ψ_{md} values increased after the rainfall events recharged the soil water (Flanagan and Ehleringer, 1992; Xu and Li, 2006; Kray et al., 2012). However, there was no significant variation in ψ_{pd} and ψ_{md} values of *Q. variabilis* from days with no rain to moderate rainfall events. On the other hand, ψ_{pd} and ψ_{md} values increased during the heavy rainfall and rainstorm events as the precipitation penetrated into the > 60 cm soil layer (Fig. 8). The results of correlation analysis also indicated that the effect of SWC in the deep layer on leaf water potential was more significant than surface soil layer (Table 3). This finding similar with Snyder and Williams (2000) and West et al. (2007), who demonstrated that tree species that predominantly rely on deep soil water or groundwater showed no significant correlation between the leaf water potential and rainfall. It was interesting to observe that the tree species using deep water sources generally have lower water-use efficiency (WUE) than the species with high precipitation uptake (a relatively unstable water source) (Flanagan and Ehleringer, 1992). This point may in part explain the water use patterns of *P. orientalis* and *Q. variabilis*. Furthermore, *P. orientalis* is an evergreen coniferous tree that grows in North China, where nearly eight months of drought are observed each year. It predominantly uses the deep water during periods with no rain, while after the rainfall events, it takes up as much precipitation as possible. On the other hand, *Q. variabilis* germinates at the end of April and loses its leaves in November. Its vigorous growing period is during the wet season (June - September) in North China. This species obtains abundant water of considerable depth, and does not need to uptake the precipitation immediately because the rainfall is not reliable. Their water use patterns can explain why both the tree species (*P. orientalis* and *Q. variabilis*) could form a relatively stable mixed forest since their plantation in 1950s. In the context of climate change, extreme drought may cause these two species to rely more on soil water. Extreme precipitation events may be more conducive to the growth of *P. orientalis* since it can use water from multiple soil layers more quickly. This may also be the reason why *P. orientalis* can grow well and spread widely in this region, even with thin soil layer. However, the current study only focused on the trees' response to water source and leaf water potential to precipitation. Further studies on stomatal conductance, WUE, and sap flow combined with water sources would provide more insights in the forest reforestation and water management in this region.

5. Conclusions

In this study, the dual stable isotopes of δ^2H and $\delta^{18}O$ were used to detect the water sources of coniferous and broad-leaved tree species, as well as their leaf water potential response to four precipitation events under different amounts of rainfall. The results indicated that the two species have different water use strategies and opposite responses to precipitation. Both species predominantly obtained water from natural springs and the deep soil layer for survival during days with no rainfall. Following the rainfall events, *P. orientalis* absorbed more water from the surface soil layers and precipitation, and the values of ψ_{pd} and ψ_{md} increased with the increase in rainfall, exhibiting sensitivity in response to precipitation. On the other hand, *Q. variabilis* mostly absorbed water from natural springs and the deeper soil layer, and the values of ψ_{pd} and ψ_{md} did not change from no rain to light rainfall events, implying that there was no response to precipitation. The ψ_{pd} and ψ_{md} values for *Q. variabilis* increased during the heavy rainfall and rainstorm events with > 60 cm soil water recharge by precipitation, which confirmed that this species is a deep water source plant. These findings suggest that *P. orientalis* can rapidly adjust its water use pattern according to the moisture conditions, exhibiting better environmental adaptability than *Q. variabilis.*

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